INFLUENCE OF THE LANGMUIR PROBE SHAFT ON MEASURING PLASMA PARAMETERS

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ABSTRACT. Because of their good spatial and temporal resolution Langmuir probes are often used for plasma diagnostics. One has to keep in mind, however, that the presence of the probe can substantially perturb the neighboring plasma.
Apart from the probe tip, in particular the probe shaft may affect the measured values of temperature and density. We have studied this latter effect at the linear plasma generator PSI-2 which provides a stationary plasma column of $2.6\,\mathrm{m}$ in length and $8\,\mathrm{cm}$ in diameter. Two single probes differently arranged were used in these experiments. In the first case the probes were in the same plane but tilted to each other in azimuthal direction. In the second arrangement the probes were separated by a distance along the magnetic field lines at the same azimuthal angle. One probe was kept at a fixed (but variable) position while the other was scanning the plasma radially.
It is found that the electron temperature is hardly influenced by the presence of the second probe, but the electron density is decreased up to 30%. The results can approximately be described in the frame of a global particle model treating the probe shafts as additional plasma sinks. Most striking is the observation that large global reductions of the density are accompanied by only moderate local changes. This means that the perturbations caused by the probe are characterized by a large scale effect, possibly indicating anomalous diffusion.

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1. INTRODUCTION

The properties of a plasma are often diagnosed by means of electrostatic probes (see [1]–[3] and references therein). Most popular are Langmuir probes [4], applied either as single, double, or triple probes. The ease of bringing the probe into plasma and obtaining a current-voltage-characteristic is partly offset by a complicated theory and interpretation of the probe characteristics. But even with the proper theory one has to keep in mind that probe measurements are invasive, i.e, the influence of the probe and its holder on the plasma cannot be neglected. While other works (e.g. [5]-[7]) investigate the electric influence of the probe tip, this study focuses on the influence of the probe shaft on the plasma parameters in a magnetized plasma. To our knowledge there exists only one publication dealing with this effect, but in an unmagnetized plasma [8].
The experiments were conducted at the linear plasma generator PSI-2 [9] which is briefly described in the next section. Also, the dimensions of the tips and shafts of the used probes and their spatial configurations in the PSI-2 are described there. Thereafter, a global particle balance model is introduced treating the probe shafts as particle sinks. We then present measured profiles of temperature and densities and compare the latter with the model predictions. The article concludes with a discussion of the applicability of the model on measured electron densities to reconstruct the true density profiles.

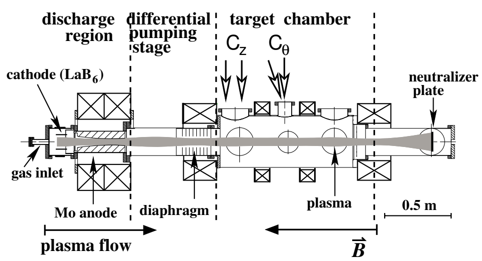

FIGURE 1. Plasma Generator PSI-2 . The two spatial probe configurations C_z and C_θ are illustrated

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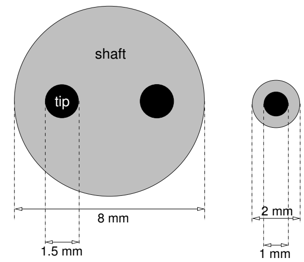

FIGURE 2. Dimensions of the Langmuir probes. Left: LP_{big}, right: LP_{small}

2. EXPERIMENTAL SET-UP

PSI-2 is a linear plasma device consisting a stationary arc discharge. A steady discharge current in the range of 20 to about 500 A can be chosen. Different working gases can be blown into the discharge region where a plasma is produced between a heated, hollow, cylindrical LaB_6-cathode and a cylindrically-shaped Mo-anode. The geometry of the discharge region results in a hollow profile in electron density and temperature ([9],[10]). Guided by an axial magnetic field the plasma streams with a typical cross-section of 80 mm through a differential pumping system and a so called target chamber and is terminated at the neutralizer plate (cf. Fig. 1). The Langmuir probes were mounted in the first and second plane of the target chamber. Parameters for this work are: $I_{\mathrm{AC}} = 100$ A, $B = 0.1$ T, $n_{\mathrm{e}} = 10^{18} \ldots 10^{19}$ m^{-3}, $T_{\mathrm{e}} = 2 \ldots 15$ eV, $T_{\mathrm{i}} = 0.5 \ldots 0.7\, T_{\mathrm{e}}$, $p_{\mathrm{neutral}} \approx 0.05$ Pa.
One of the probes (LP_{big}) can be used as a double or a single probe and consists of two tungsten tips ($h = d = 1.5$ mm) attached to a ceramic shaft (diameter $D = 8$ mm). The other one (LP_{small}) consists of one tip ($h = d = 1$ mm) embedded in a ceramic shaft ($D = 2$ mm). The presented results of LP_{big} refer to cases where it was used as single probe.

In each configuration one probe was kept at a fixed (but variable) position while the other was scanning the plasma radially. Both probes were interchanged in each configuration. To anticipate part of the results, the influence on density were in both configurations about the same.

3. GLOBAL PARTICLE BALANCE

We consider a cylindrical plasma column (radius a, length L) radially confined by a magnetic field. A stationary plasma is maintained by a production rate due to ionization within the volume $\dot{N}_{\mathrm{ion}}$ and an influx Φ_{in} from the left hand side and a compensating outflux

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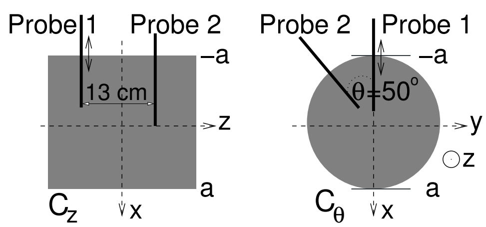


FIGURE 3. Geometrical configurations C_z (*left*) and C_θ (*right*)

To identify the effects caused by an axial distance or an azimuthal angle separating the two probes, we arranged them in the two different configurations shown in Fig. 3. In configuration C_z both probes are axially separated by a distance of $13\,\mathrm{cm}$ along the magnetic field lines with the same azimuthal angle. In configuration C_θ both are arranged in the middle plane of the target chamber but tilted to each other in the azimuthal direction by an angle of $50\,^\circ$.

Φ_{out} of particles at the neutralizer plate and the right hand end. No outflux perpendicular to the magnetic field nor recombination within the volume is be taken into account.

Without a disturbing probe the particle balance reads

$$\dot{N}_{\text{ion}} + \Phi_{\text{in}} = \Phi_{\text{out}} \ = \int_0^a \Gamma(r) 2\pi r \ \mathrm{d}r \tag{1}$$

where the particle flux density is given by $\Gamma = 0.5\ n_{\text{e}} \sqrt{k(T_{\text{e}} + T_{\text{i}})/m_{\text{i}}}$.

If a probe is inserted into the plasma its surface provides a sink for the plasma particles which can be taken into account by an additional flux Φ_{loss} on the right hand side of the balance equation. Assuming that the probe enters along the negative part of the x-axis and its tip has reached the position $x = x_1$ the corresponding losses amount to

$$\Phi_{\text{loss}} = 2D \int_{-a}^{x_1} \Gamma(|\xi|) \mathrm{d}\xi \ , \tag{2}$$

where D is the diameter of the probe shaft and it has been assumed that the parallel particles fluxes in the $+z$ and $-z$ directions are equal. Let us further assume that neither the influx nor the plasma production is changed by the probe and thus the left hand side of Eq. (1) stays constant. We then have the relation $\Phi^{\text{un}}_{\text{out}} = \Phi^{\text{dis}}_{\text{out}} + \Phi_{\text{loss}}$ or explicitly

$$\int_0^a \Gamma^{\text{un}}(r) 2\pi r \ \mathrm{d}r = \int_0^a \Gamma^{\text{dis}}(r) 2\pi r \ \mathrm{d}r + 2D \ \int_{-a}^{x_1} \Gamma^{\text{dis}}(|\xi|) \mathrm{d}\xi \tag{3}$$

where the superscripts un and dis refer to the undisturbed and the disturbed case, respectively. The last balance can be specified further by anticipating the experimental findings that (i) the temperatures are not affected by the probe and (ii) the normalized density profiles are equal in the two cases. The flux densities can then be written as $\Gamma^{\text{un}} = \Gamma^{\text{un}}_0\ \gamma(r)$ and $\Gamma^{\text{dis}} = \Gamma^{\text{dis}}_0\ \gamma(r)$ with the normalized profile

$$\gamma(r) = \frac{n_{\text{e}} \sqrt{(T_{\text{e}} + T_{\text{i}})}}{n_{\text{e}0} \sqrt{(T_{\text{e}0} + T_{\text{i}0})}} \tag{4}$$

such that $0 \leq \gamma(r) \leq \gamma(r_0) = 1$. Equation (3) can then be solved for the ratio of the maximum flux densities $\Gamma^{\text{dis}}_0 / \Gamma^{\text{un}}_0$ which, however, coincides with ratio for the density maxima in the two cases $n^{\text{dis}}_0 / n^{\text{un}}_0$. This ratio still depends on the probe position. It is therefore convenient to define the function $\tilde{n}_0(x_1) := n_0^{\mathrm{dis}}/n_0^{\mathrm{un}}$. The result reads

$$\tilde{n}_0(x_1) = \frac{\int_0^a \gamma(r) r \mathrm{d}r}{\int_0^a \gamma(r) r \mathrm{d}r + \frac{D}{\pi}\int_{-a}^{x_1} \gamma(|\xi|)\mathrm{d}\xi} \; . \tag{5}$$

There is no difficulty to extend this result to the case when two probes are simultaneously disturbing the plasma

$$\tilde{n}_0(x_1, x_2) = \frac{\int_0^a \gamma(r) r \mathrm{d}r}{\int_0^a \gamma(r) r \mathrm{d}r + \frac{D_1}{\pi}\int_{-a}^{x_1} \gamma(|\xi|)\mathrm{d}\xi + \frac{D_2}{\pi}\int_{-a}^{x_2} \gamma(|\xi|)\mathrm{d}\xi} \; . \tag{6}$$

4. EXPERIMENTAL FINDINGS

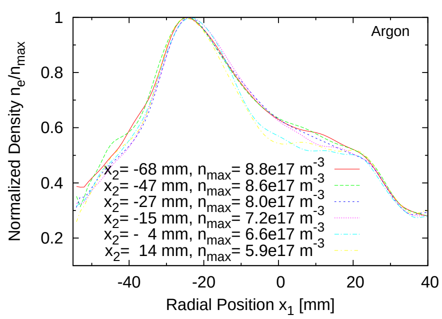


FIGURE 4. Density profile taken with one probe (x_1) while the other one was set to x_2. Argon plasma, configuration C$_\theta$ ($D_1 = D_2 = 8$ mm).

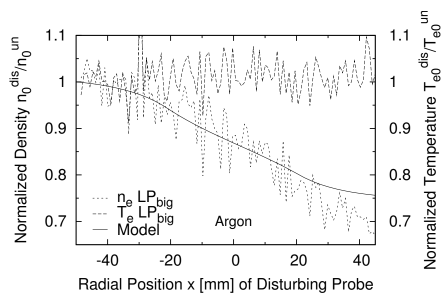
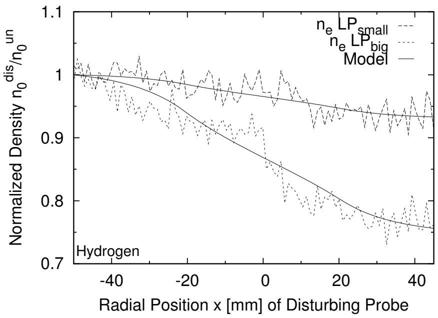


FIGURE 5. Measurement of the central electron density and temperature in an argon plasma in configuration C$_\theta$ ($D_1 = D_2 = 8$ mm). The solid line indicates the prediction according to Eq. (5).

In Fig. 4 the first probe scans the whole plasma cross-section starting at large negative x-values while the other one is set to a particular position x_2 in configuration C$_\theta$. For comparison each individual density profile is normalized by its peak density. It can be seen that the profile shape is nearly unchanged while the absolute density decreases substantially with rising x_2.

In Fig. 5 the electron density and temperature are taken by probe 1 at the central position while probe 2 is driven radially through the plasma starting from negative x-values. This was done in configuration C$_\theta$. Probe 1 causes a constant distortion, while probe 2 acts as a particle sink implying a variable distortion. For a better comparison the disturbed density and temperature, respectively, is divided by the undisturbed one. It can be seen that the temperature, in contrast to density, stays about unchanged when the second probe penetrates the plasma.



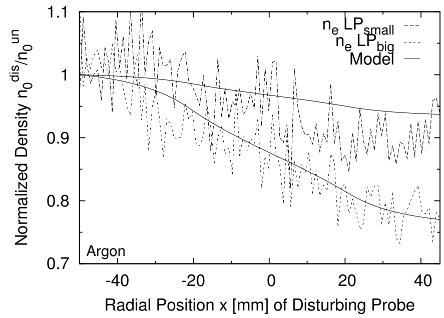


FIGURE 6. Hydrogen (*left*) and argon (*right*) in configuration C_z. A Langmuir probe at $x = 0$ position measures the electron density while a floating disturbing probe (large or small according to label) is driven radially across the plasma. The solid curves indicate the model predictions.

In Fig. 6 the two different shaft sizes are compared in configuration C_z for both working gases. The results for the two working gases are about the same. In case of the big Langmuir probe shaft (LP_{big}) the electron density is reduced by 25%. The reduction in case of the small probe shaft (LP_{small}) is about 6%. Moreover, no major differences between the two configurations C_z and C_θ are found.
The above experimental findings suggest that the decrease of density caused by a probe shaft is in some way universal, i.e. independent of the geometrical configuration and the working gas.
The next section addresses the density profile in the PSI-2 that were used in the global particle model to calculate the solid lines in the figures.

4.1. **Density profiles in PSI-2.** The radial density profiles found in PSI-2 are quite well approximated by the expression

$$n_e(r) \ = n_e(r_0) \cdot B_0(r) = n_e(r_0) \begin{cases} I_0(kr)/I_0(kr_0) & r \le r_0 \\ K_0(kr)/K_0(kr_0) & r > r_0 \end{cases}, \tag{7}$$

which follows from an analytical treatment assuming anomalous diffusion and a shell like plasma source at $r = r_0$ (see [10]) and with $r = |x|$. Here k and $n_e(r_0)$ are fitting parameters and I_0 and K_0 are the modified Bessel functions.

Comparisons with typical measured profiles are shown in Figs. 7 & 8. The electron density is measured by a Langmuir probe starting at large negative x-values. The fitted profiles are used to describe the radial dependence in Eqs. (5) and (6). In the profile wings, where the density becomes very low, there is the tendency by the probes to yield too large values. This has been revealed by using probes with large tips (high saturation currents) in these regions. The nearly constant density for $x < -40\,\mathrm{mm}$ to be seen in Fig. 7 is also attributed to this effect.

4.2. **Reconstruction of the true profiles.** Fig. 9 shows the results obtained this way. Obviously the corrections provided by the model are too weak to enable a compensation of the strong asymmetries occurring in the measured density profiles. The profile $(+)$ is measured starting from negative x-values. Applying our model with the real probe diameter of $D = 8\,\mathrm{mm}$ to the measured values leaves the profile nearly unchanged $(\times)$. Enhancing

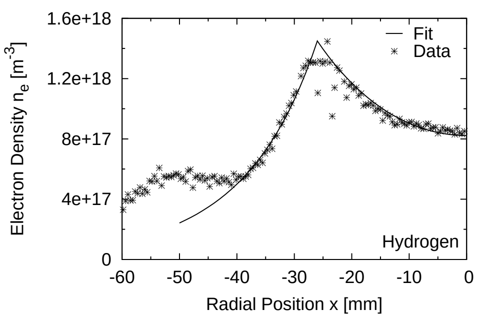


FIGURE 7. Radial density profile in **H** ($k = 62\,\mathrm{m}^{-1}$, $\mathrm{r}_0 = 0.027\,\mathrm{m}$, $n_{\mathrm{e}}(r_0) = 1.45 \cdot 10^{18}$ m^{-3}).

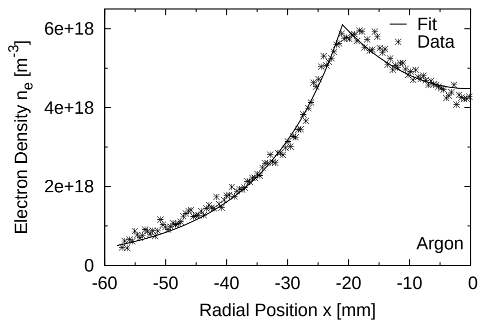


FIGURE 8. Radial density profile in **Ar** ($k = 55\,\mathrm{m}^{-1}$, $\mathrm{r}_0 = 0.021\,\mathrm{m}$, $n_{\mathrm{e}}(r_0) = 6.1 \cdot 10^{18}\,\mathrm{m}^{-3}$).

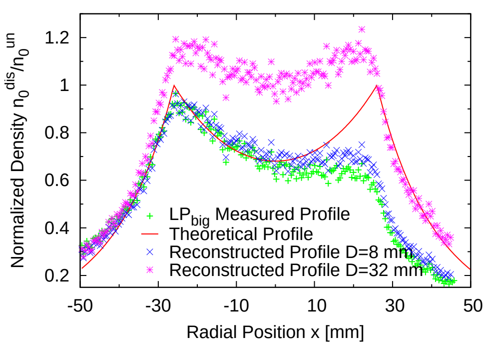


FIGURE 9. Density profile in argon measured with $\mathrm{LP}_{\mathrm{big}}$. The profile was corrected with the global particle model to compare it with the predicted profile which is plotted as a solid curve. $D = 8\,\mathrm{mm}$ and $D = 32\,\mathrm{mm}$ was used for correction.

The good agreement between the measured disturbances and those predicted on the basis of the global particle model is encouraging to reconstruct the true profiles from the measured ones. This may be simply achieved by inverting the relation (5). Whether such an attempt is successful or not may be judged from shape of the profiles attained this way. Indeed, we have strong indications that the genuine profiles are radially symmetric. This is expected on one hand from the fact that the plasma is rapidly rotating [12], but also the Langmuir profiles of electron temperature and floating potential are found to be symmetric. Finally, launching probes along the positive x-axis corroborate this statement too. artificially the probe diameter up to $D = 32\,\mathrm{mm}$ renders the reconstructed profiles more symmetric but flattens simultaneously the inner hollow part of the profile ($*$). The theoretical profile is shown for comparison. We thus have to conceive that our simple model is only a first approach and needs further improvements.

5. SUMMARY

It is found that the shaft of a Langmuir probe behaves as an additional particle sink and reduces the electron density of the plasma. Interestingly, it has nearly no impact on electron temperature.

The observation that the plasma is distorted mainly in a global way and less locally is a crucial one and allows a first quantitative analysis of the measured results invoking a simple model.
Corrections of the measured data basing on the same model (Eq. (5)) are not yet satisfying, however, thus calling for further improvements.
The strong global influence is indicative that the perturbations occur on a large scale, presumably indicating anomalous diffusion.

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